Navigating Across the C-band

Experimental C-band Intensives with the VLBA

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Abstract The US Naval Observatory makes daily UT1 Intensive observations on the Mauna Kea–Pie Town (MkPt) baseline of the Very Long Baseline Array (VLBA) using the standard S/X bands in a bandwidth synthesis mode. These observations are increasingly negatively impacted by RFI in the S-band. The frequency range of the S-band receiver is no more than 256 MHz wide, restricting the ability to place the 32 MHz wide channels to avoid the RFI. The VLBA C-band receiver is more sensitive and has a wide frequency range (3.9–7.9 GHz) which allows for more flexibility in the placement of channels. To see if the difficulties encountered in the S-band can be overcome by using the C-band, we have undertaken two experiments using the C-band receiver on the Hancock–Owens Valley baseline of the VLBA. The first is a standard group delay observing setup accomplished by placing channels at the low and high ends of the C-band frequency range as analogs of the S- and X-bands. A major question here is whether the smaller frequency separation is sufficient for ionosphere calibration. The second is an attempt at broadband group delay measurement across the width of the C-band. Here we present the design of these sessions and preliminary results.

Keywords VLBA, C-band, Intensives, Broadband

United States Naval Observatory

1 Introduction

For several years the United States Naval Observatory (USNO) has been making daily Intensive observations using the Very Long Baseline Array (VLBA), which is operated by the Long Baseline Observatory. These 90 minute sessions use the Mauna Kea and Pie Town stations, which have optical fiber connections, allowing for fast data transfers resulting in latencies of less than half a day. So far, the session design was modeled on the IVS Intensive series. The setup uses six S-band channels and ten X-band channels in single polarization. Unlike in the IVS Intensives, the channels are 32 MHz wide, the widest that the VLBA can accommodate with 16 channels using the polyphase filter bank (PFB) personality, providing a total data rate of 2 Gbps. The VLBA scheduling software SCHED does not allow for a scan duration to be a function of the brightness of the source, so all scans record data on source for 16 seconds. This duration provides a good compromise between data volume and an adequate SNR for most sources.

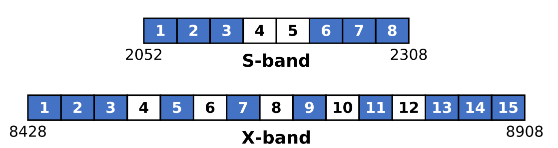

Fig. 1 The channel spacing for the current S/X VLBA Intensives, with the bounding frequencies labeled in MHz. The channels are 32 MHz wide, and those in blue are observed.

The existing setup has worked well but poses some problems as we look to the future. At the Mauna Kea and Pie Town stations, the available bandwidth of the S-band receiver is only 256 MHz, and, as can be seen in

Figure 1, there are only so many ways that six channels can be placed in this range. Currently, S-band channels 2 and 3 are regularly being dropped due to RFI, and there is no better way to arrange the channels in the available frequency space to retain a greater number of channels. Additionally, the RFI environment in the S-band is likely to deteriorate in the future as additional telecommunications infrastructure becomes operational. Furthermore, the available S-band bandwidth at the other eight VLBA stations is even less than that at Mauna Kea and Pie Town due to filters that are in place to keep RFI from swamping the amplifiers. If these observations were to be extended to other stations, which they already are for backup observations, S-band channel 1 would also be deselected because of the filters.

Currently, the most sensitive receiver available on the VLBA is the recently upgraded C-band receiver. It has a wide bandwidth of 4 GHz, spanning the frequency space between the S- and X-band receivers. These features make it a potential alternative to the S/X setup by using the low end of the C-band as an analog for the S-band and the high end of the C-band as an analog for the X-band. The purpose of the investigation described herein is to see whether or not Intensive sessions observed with the C-band receiver can perform as well as, or better than, the current S/X sessions and do so at all VLBA stations now and/or in the future.

2 Observations

2.1 Initial Test Session

Before embarking on a larger campaign to test the characteristics of sessions observed in the C-band, we first needed to test that such sessions could be scheduled, observed, correlated, fringed, and analyzed. To accomplish this, we ran a single observation in November of 2017 where everything was the same as the standard S/X setup except that the frequencies were different. The S-band became C-low, from 3,928–4,408 MHz, and the X-band became C-high, from 7,392–7,872 MHz.

This session was successfully shepherded through the process of making an estimate of UT1$-$UTC, and the values of UT1$-$UTC and its uncertainties were consistent with the other Intensive sessions observed around that time. However, given that the C-high and C-low mean frequencies are only separated by $\sim$3.5 GHz (compared to $\sim$6.5 GHz for the S/X mean frequencies) there may be an impact on the accuracy of the ionosphere correction. A small complication was that the Mark III database files required an atypical naming scheme to identify them as being associated with C-band data rather than S/X data. With only small obstacles and success in making the observation, further investigation was possible and warranted.

2.2 Typical Group Delay Sessions

After the initial test, we wanted to develop a setup from scratch that met some overarching design goals. First, we wanted to be able to compare the UT1$-$UTC value against another VLBA baseline that was observed at the same time. We also wanted a setup that mimicked the S/X approach and that kept as large a separation as possible between the two new subbands at the ends of the C-band. We also had to be careful about the channel spacing so that the fringe function would have a strong central peak with low side lobes. If possible, placing the channels so that the two subbands would have different ambiguity spacings would be a bonus.

Working within the constraints of the VLBA backends, we developed the following setup. The observations would be made on the longest east-to-west continental US baseline, Hancock–Owens Valley (HnOv), at the same time as the standard S/X MkPt VLBA daily Intensives. This meant that the difference between the UT1$-$UTC values would hopefully be able to be directly compared, and that the Intensive sessions were only interrupting the VLBA once. The digital down converter (DDC) personality allows for more flexible channel placement than the PFB personality, enabling us to achieve both different ambiguity spacings between bands and accessing the extremes of the range of the C-band receiver. However, this also limited us to using four 32 MHz channels with single polarization in each of the C-low and C-high bands.

To keep as many channels as possible towards the edges of the receiver's range while still keeping a reasonable fringe function, the channels were spaced using a Golomb ruler of order 4 and then placed at either end of the C-band. Though the channels at both C-low and C-high were still 32 MHz wide, the C-low channel edges were spaced at multiples of 40 MHz apart whereas the C-high channels were spaced at multiples of 32 MHz to make the ambiguity spacings different between the bands. The resulting fringe functions are shown in Figure 2. The lower edge frequencies of the C-low channels were 3,912, 3,952, 4,072, and 4,152 MHz while the lower edge frequencies of the C-high channels were 7,664, 7,728, 7,824, and 7,856 MHz, as shown in Figure 3. With only eight channels each 32 MHz wide in a single polarization, the data rate was 1 Gbps. Though not making up for the difference in data rate entirely, the scans were observed for twice as long as in the standard S/X setup, an on source duration of 32 seconds.

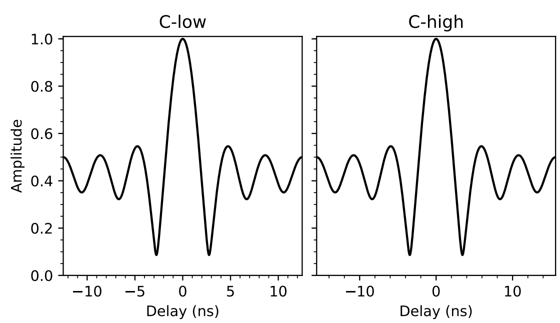

Fig. 2 The shapes of the normalized theoretical fringe functions of the typical group delay setup. The shape of the fringes is the same, but they have different widths, 25.0 ns for C-low and 31.25 ns for C-high.

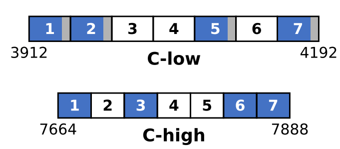

Fig. 3 The channel spacing for the C-band typical group delay setup, with the bounding frequencies labeled in MHz. The blue channels are those that were observed. The portion of the C-low channels that was not recorded is in gray. The widths of the channels are 40 MHz in C-low and 32 MHz in C-high.

2.3 Broadband Group Delay Sessions

In contrast to the typical group delay setup, we also wanted to develop a setup that would be better suited to fit the phase as a function of frequency across as much of the C-band as possible. Using the DDC personality we were able to place four channels, each 128 MHz wide, across the C-band with single polarization. However, rather than have them equally spaced, or some other particular placement, the channels had to be placed in pairs at the high and low ends of the C-band with a separation of 256 MHz between the channels in each pair, as shown in Figure 4. The data rate was 2 Gbps, so on source time was reduced back to 16 seconds. These observations were also observed at the same time as the standard S/X Intensives. With four 'bands' extracted from a wideband receiver, this setup is very similar to the full planned VGOS observations.

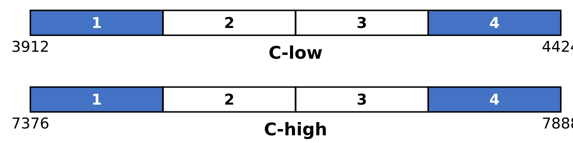

Fig. 4 The channel spacing for the C-band broadband group delay setup, with the bounding frequencies labeled in MHz. The channels are 128 MHz wide, and those in blue are observed.

3 Results

3.1 Typical Setup Results

The analysis of the sessions observed with the typical group delay setup is ongoing. There were 26 sessions observed from April 11 to June 28, 2018, of which ten were processed. These ten sessions were correlated, fringed, and packaged into the Mark III database format. From observation to having a database takes about two weeks. They were then analyzed in νSolve in the way that the IVS Intensives are analyzed. First, any ambiguities are resolved, and a group delay solution is fit at both the high and the low bands. Then the ionospheric corrections are calculated and applied, followed by scan uncertainty reweighting and outlier elimination. Of the ten analyzed sessions, only six have data that are useful for developing an understanding of the characteristics of the setup. The other four were either not observed at the same time as the S/X VLBA Intensive, the VLBA S/X Intensive used a baseline other than MkPt, or the C-band session output was aberrant. The UT1−UTC values and uncertainties from these six sessions are given in Table 1 along with the uncertainties of the IVS Int1 and VLBA S/X Intensives for each of those days of the year.

Table 1 Analysis results and comparison of the group delay test sessions to the IVS and standard VLBA sessions on the same day of the year (doy). ΔUT1−UTC is the standard S/X VLBA session UT1−UTC minus the C-band session UT1−UTC. The rss is the root of the sum of the squares of the S/X and C-band σs.

DOY, 2018	IVS σ (μs)	S/X σ (μs)	C-band σ (μs)	ΔUT1−UTC (μs)	rss σ (μs)
111	7.0	20.6	13.4	94.3	24.6
115	6.5	13.0	33.4	81.7	35.8
124	6.8	7.1	34.4	−3.6	35.1
125	8.6	11.6	64.6	118.0	65.6
127	7.1	8.6	20.5	133.5	22.2
128	7.7	13.2	31.1	171.9	33.8
Mean	7.3	12.4	32.9	99.3	—

If we are to judge the success of these sessions based on their reported uncertainties, then they are not doing very well. With the mean uncertainty of the C-band sessions ~2.5 times that of the standard VLBA S/X, this does not seem like a setup that would provide a better estimate of UT1−UTC than the one already in use. However, more sessions are necessary to make the statistics more meaningful. Also, the setup is better judged by the wrms of the UT1−UTC residuals to a reference series, such as the IERS Bulletin A.

Looking at the mean value of the difference in UT1−UTC from the S/X sessions to the C-band sessions, there is some systematic offset that needs to be taken into account. This is not unexpected because the measurements are made at different baselines. Additionally, the east-west component of the HnOv baseline is 3,856 km, where the same value for the MkPt baseline is 4,579 km. This difference in baseline length contributes to the increased uncertainty in the C-band sessions, so in addition to developing different statistics, it would be better if the C-band sessions were compared to the same baseline. Luckily, there are several months of standard S/X observations on the HnOv baseline from which to develop metrics for comparison. However, this comparison is left for future work.

Exploring an individual session, such as that from the 115th day of the year, we can see some other effects of the C-band setup. As noted above, the uncertainty

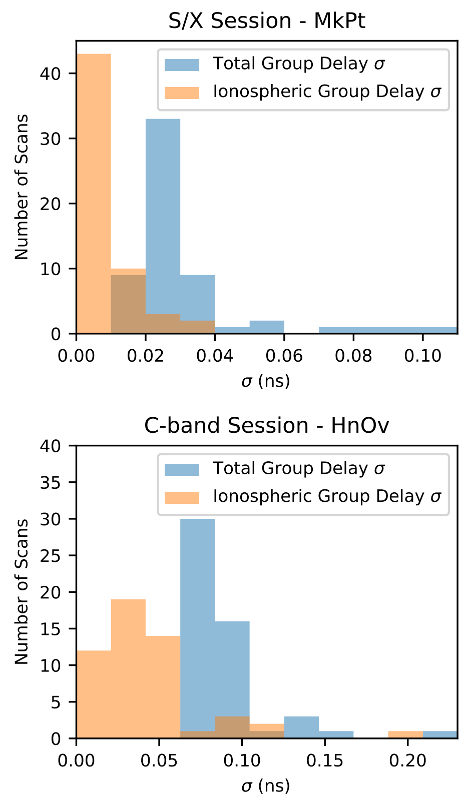

Fig. 5 Histograms showing the number of scans with total reweighted group delay uncertainties in blue and ionosphere correction uncertainties in orange for the MkPt S/X session (top) and the HnOv C-band typical session (bottom) on doy 115.

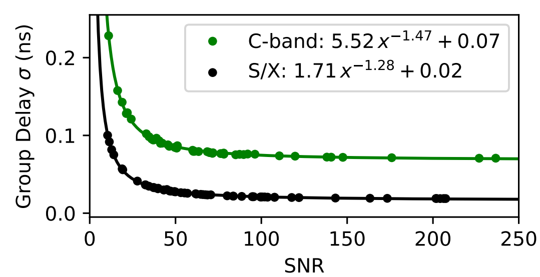

Fig. 6 Total reweighted group delay uncertainty per scan as a function of SNR for doy 115 for both the typical group delay setup on HnOv and the standard S/X session on MkPt. The functional form of the fit for both sessions is given in the legend.

is elevated over that of the S/X VLBA session. However, as is shown in Figure 5, the distribution is pretty similar; it is just the scale that is larger. This is corroborated by looking at the uncertainty as a function of scan

SNR, shown in Figure 6. One of the concerns regarding this setup design was whether or not the smaller distance between the two bands would allow for good ionospheric corrections. Figure 5 suggests that the uncertainty from the ionospheric correction in the C-band setup contributes more to the total uncertainty than in the S/X setup. This is supported by the mean of the ratio of the ionospheric correction uncertainty to the total uncertainty for each setup, which is 25.9% for the S/X setup and 43.0% for the C-band setup. It may be that C-high and C-low are too close together for useful ionosphere calibration in the typical setup.

3.2 Broadband Setup Results

For the broadband group delay setup, 15 observations were made, but only two have been processed. The processing of these two has been in the same manner as for the typical group delay. Though this was not the intended analysis when the setup was designed, it was executed to allow for a comparison between the analysis approaches. The output of these two sessions show uncertainties similar to the IVS Intensives, but the metrics are not very meaningful without a larger sample. The main conclusion from the analysis so far is that this setup shows promise, particularly over the typical C-band setup. All 15 sessions will be analyzed in this way and compared with the standard S/X and the typical C-band setups, but it is the potential to use each of the four channels on its own that makes this setup interesting, although new software may need to be developed.

4 Future Work

Though inconclusive at this stage of analysis, these initial results suggest that Intensives made with the C-band receiver on the VLBA may prove to be useful in the future. It appears that the broadband setup, rather than the traditional group delay setup, may be a better approach to incorporating the C-band. Before anything can be said with certainty, though, the analysis of the sessions already observed needs to be completed. There are also a few more calculations that can be applied to evaluate the results more effectively. For the typical group delay setup, calculating any bulk offset in UT1−UTC between the C-band series and the standard S/X series will allow for better comparison between the two. The uncertainties of the UT1−UTC estimates are dependent on the baseline length between the stations, and accounting for this when comparing the different session series will be illuminating.

With only 15 observations of the broadband setup, additional sessions will need to be obtained to achieve better statistics, perhaps with modifications to make the spacing of the channels within the band better suited to making an estimate of the differenced total electron content (dTEC). Additionally, we need to develop a way of using the four channels to actually do a broadband fit.

These analyses are currently based on the assumption that source positions defined in the X-band celestial reference frame are appropriate for use with observations made at C-high. The difference in mean frequency between these two bands is $\sim$1 GHz (8.6 GHz for X-band and 7.6 GHz for C-high). Though any induced offsets in UT1−UTC due to unaccounted shifts in the source position (e.g. core shift) are likely to be within the uncertainty, the validity of this assumption needs to be verified.

Regardless of the work that has yet to be performed, this investigation already demonstrates that the flexibility, rapid scheduling, and relatively short latency from observation to creating a database makes the VLBA a facility that can be effectively used to try out new approaches to geodetic and astrometric observations and data analysis. This could prove to be useful in the transition to and during the VGOS era.

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